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The achievements and the research results of our research program for the past three years arc summarized in this final report. We have developed new methods to robust model identification and robust control design for complex nonlinear uncertain systems with Air Force problems as application platforms. The primary focus of our research program has been on rotating stall and combustion instabilities which are the two primary constraints for performance improvement of future aeroengines. Both involve complicated flow patterns, and exhibit rich nonlinear dynamics with non-equilibrium steady state behavior. We have developed new modeling and control algorithms to approach nonlinear oscillatory systems. For compressor control, we employed bifurcation stabilization approach, and are able to control rotating stall for the multi-mode MooreGreitzer model. For combustion control, we are able to apply $H^{\sim}$ robust control method to suppress nonlinear vibrations. Our research results have benefited Air Force Research Labs. in WPAFB, and aeroengine industry. For fault detection/identification, and reconfigurable flight control, we also made great progress. A new feedback control architecture has been developed that has the potential to overcome many conflicting problems in standard feedback control and provide a unified framework for robust and fault tolerant control. In addition we have made progress in system identification and robus control for several important aspects that will be described in this final report. The research objectives as proposed in our proposal have been accomplished successfiilly as demonstrated in the 30 journal publications, one book, two book chapters, and 25 conference papers we have had for the past three years, including those accepted for publication.

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Abstract

The achievements and the research results of our research program for the past three years are summarized in this final report. We have developed new methods to robust model identification and robust control design for complex nonlinear uncertain systems with Air Force problems as application platforms. The primary focus of our research program has been on rotating stall and combustion instabilities which are the two primary constraints for performance improvement of future aeroengines. Both involve complicated flow patterns, and exhibit rich nonlinear dynamics with non-equilibrium steady state behavior. We have developed new modeling and control algorithms to approach nonlinear oscillatory systems. For compressor control, we employed bifurcation stabilization approach, and are able to control rotating stall for the multi-mode Moore-Greitzer model. For combustion control, we are able to apply H_∞ robust control method to suppress nonlinear vibrations. Our research results have benefited Air Force Research Labs. in Wright-Patterson Air Force Base, and aeroengine industry. For fault detection/identification, and reconfigurable flight control, we also made great progress. A new feedback control architecture has been developed that has the potential to overcome many conflicting problems in standard feedback control and provide a unified framework for robust and fault tolerant control. In addition we have made progress in system identification and robust control for several important aspects that will be described in this final report. The research objectives as proposed in our proposal have been accomplished successfully as demonstrated in the 30 journal publications, one book, two book chapters, and 25 conference papers we have had for the past three years, including those accepted for publication. The educational objective is accomplished as well. Three Ph.D. students, and five M.S. students have been supported partially in completion of their degrees in 1999, 2000, and 2001 respectively. With the strong control program established in the ECE Department at LSU, we are confident to contribute further to the DoD mission in the near future.

Objectives

The proposed research focuses on novel approaches to system identification and robust control for nonlinear uncertain systems, and development of new methods for active control of jet engines, reconfigurable flight control, and other Air Force application problems in aerospace vehicles. The primary goal of this research program is to develop a number of advanced, both theoretically sound and practically useful identification and control techniques applicable to complex nonlinear uncertain systems. The proposed research includes (1) developing modeling and control methods for limit cycling systems applicable to solving combustion instabilities, and rotating stall problems; (2) developing model validation and parameter identification algorithms for nonlinear bifurcation and oscillatory systems which are common in turbomachinery aeroengines; (3) developing a more general and integrated approach to robust identification and optimal control for nonlinear complex systems of which modeling error is inevitable; (4) developing novel techniques and algorithms for detection, diagnosis of sensor and actuator failure under the framework of multi-objective optimal estimation to enhance robustness; and (5) developing on-line adaptive algorithms for innovative nonlinear adaptive control suitable for reconfigurable flight control.

We have made significant progress towards achieving the objectives of our proposed research. We have obtained results in (1) H_∞ based robust adaptive control; (2) Modeling and control for rotating stall and surge in axial flow compressors in aeroengines. (3) Identification and robust control of combustion instability; (4) strong stabilization techniques that are key to the design of combustion control problem; (5) new feedback control architecture that has the potential to overcome many conflicting problems in standard feedback control and provide a unified framework for robust and fault tolerant control; (6) multiple objective filtering and control techniques; (7) Robust stability analysis and control of time delay systems common in combustion dynamics; (8) Model validation for unstable uncertainty models in form of linear fractional transformation; (9) Asymptotic properties for H_∞ identification; (10) Fast and parallel algorithms for robust stability margins; (11) Control effectiveness estimation and reconfigurability estimation; (12) Inner-outer and spectral factorization for strictly proper transfer matrices; (13) Satellite formation under J2 effect; (14) Optimal Hankel-norm approximation for model reduction of discrete-time systems with error bounds; (15) Optimal channel equalization in multiuser data networks; (16) Optimal multiuser detection for CDMA networks; (17) H_∞ Gaussian filtering in infinity time horizon: (18) H_∞ Gaussian filtering in infinity time horizon. These results are summarized in 30 journal publications, and 25 conference papers listed in the publication section. We believe that we have completed our proposed research project successfully, reached our research goals as planned in our proposal, and made substantial contributions to the Air Force missions.

1. Introduction

Rotating stall and combustion instabilities are the two primary constraints for performance improvement of future aeroengines. Both involve complicated flow patterns, and exhibit rich nonlinear dynamics with non-equilibrium steady state behavior. A common feature of combustion instabilities and engine stall is the limit cycling behavior. However little was known in the area of model identification/validation and active control for limit cycling systems. Thus our research program has focused on developing new methods to robust model identification and robust control design for complex nonlinear uncertain systems with the Air Force problems as application platforms. Fault detection/identification, and reconfigurable flight control are two other motivating examples for our proposed research program. The failure in sensors and actuators can drastically change the performance of a system or even result in instability of the system, which could cause tremendous damage to the system and loss of life. This is particularly true for a defense related control system such as combat aircrafts, missile defense systems, intelligence satellites, and etc where high performance but less redundant/backup systems are used.

Our research program began in April of 1999. We have focused on three different aspects in our research work. The first is the compressor control. We have adopted a bifurcation approach to rotating stall and surge control, and innovative approaches to system identification and robust control to solve this important Air Force problem. The second is the combustion control. We have developed new modeling and control algorithms based on H_∞ robust control to suppress combustion instabilities. The third is fault detection and reconfigurable control. We have made important progress and developed a new feedback control architecture that has the potential to overcome many conflicting problems in standard feedback control and provide a unified framework for robust and fault tolerant control. Through hard work, and close collaborations with Air Force Research Laboratories, we have successfully completed most of the proposed research plan under a small budget compared with the comparable programs in the nation. Our main contributions are in the problem areas of compressor control, combustion control, fault detection and tolerance control, multi-objective control and filtering, H_∞ identification and model validation, which will be discussed in more details in the next section.

The PIs have also strived to enhance the application part of our research program. Guoxiang Gu visited Wright-Patterson Air Force base frequently in the past three years. Most of the research papers in compressor control are the results of collaborations with the control group lad by Dr. Siva Banda in the Wright-Patterson Air Force. This is due to the fact that compressor control is an Air Force problem, critical to the Air Force mission. Our main contribution in this regard is the bifurcation approach to stabilization of flow instabilities such as rotating stall and surge that was shown to be effective not only for the low order Moore-Greitzer model, but also for the multi-mode compressor model. Another important contribution to aeroengine control is suppression of combustion instabilities. Kemin Zhou has collaborated with industry, and applied optimal robust control method to control vibrations in combustors. Our control strategies showed the clear advantages over

the conventional phase delay control techniques that have been used in the most of combustion experiments in the area. These tests were actually the first success in the area of using H_∞ robust control techniques for a large power combustor (>100KW). Most of the existing work are either computational or for very small power combustors. Another advantage of our design techniques over the conventional techniques such as phase delay control is that the controller seems to be very robust in the sense that the performance is mostly preserved under various operating conditions. Our other contributions include the development of new framework for H_∞-based robust adaptive control, and fault detection and reconfigurable control. New feedback control architecture has been proposed that has the potential to overcome many conflicting problems in standard feedback control and provide a unified framework for robust and fault tolerant control. The proposal on uncertainty equivalence principle enables the development of H_∞-based robust adaptive control. In addition we have obtained new results on multiple objective filtering and control techniques, robust stability analysis and control of time delay systems, fast and parallel algorithms for robust stability margins, control effectiveness estimation and reconfigurability estimation, model validation for uncertainty systems in the form of linear fractional transformation.

This program would like to thank the Program of Dynamics and Control, AFOSR for giving us the opportunity to contribute to Air Force missions, and to thank control group in Wright-Patterson Air Force Base, led by Dr. Siva Banda for collaboration, and support to the PIs. This final report summarizes our achievements in both research and education during the past three years, and describes in details the results obtained by our research program. Our research findings will be reported in the next section.

2. Accomplishments/New Findings

Since the inception of our program on April 1, 1999, the research effort of our program has focused on identification and control of nonlinear oscillatory systems with focus on compressor control and combustion control in our application research, on fault detection and reconfigurable control, and on development of new adaptive control systems which possess both robust stability and performance comparable to H_∞-based robust control. Although our research program had a duration of three years, we have accomplished more than what we proposed initially. Our results cover not only modeling and control for nonlinear systems, but also communication based digital signal processing. In the next five subsections our accomplishments and new findings will be described in more details.

2.1 Rotating Stall and Surge Control

Feedback control was proposed first Epstein *et al.* [EFG] to improve the compressor performance, and has since received great attention in recent years. The existing results include linear control law [PEVGG], bifurcation stabilization [LA], and backstepping method [KPPK], [BHM]. Our work has focused on rotating stall control based on the

multi-mode Moore-Greitzer model [MSG], which in the limiting case converges to the full PDE model of Moore and Greitzer [MG]. We have pushed our bifurcation stabilization results to the fullest which produce the feedback stabilization results for the multi-mode Moore-Greitzer model. Our results are published in [BGSB]. It was shown that the critical operating point at the peak pressure rise of the performance characteristic curve is locally stabilizable with the proposed feedback control laws. A necessary and sufficient condition was derived for local stabilization of the underlying feedback system. This condition holds, and results in lumped feedback controllers for the full PDE Moore-Greitzer model in the limiting case. In contrast to the global stabilization results of [BHM], our local stabilization condition is explicit, and provides an effective synthesis tool for rotating stall control without distributed sensors. Hence our result compliments those of [BHM].

Feedback stabilization of rotating stall was also studied in [GS] with a special nonlinear feedback control law:

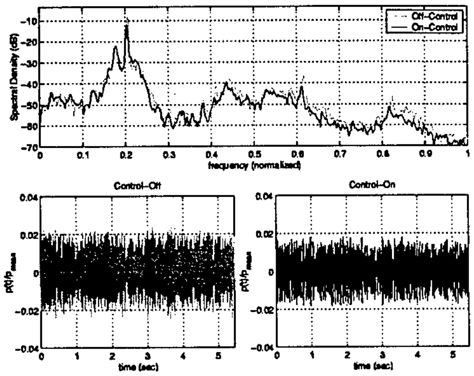
$$\delta\gamma = K / \sqrt{\Psi}$$

where $\delta\gamma$ is the actuator implemented with throttle, and Ψ the pressure rise. Its advantage lies in the use of pressure rise, without measuring the local flow rate. The local stabilization was proven for the full PDE model of Moore-Greitzer in the limiting case as well. It has the appealing to surge control in the sense that the nonlinear feedback gain gives the trade-off between surge control and rotating stall control, although the control authority may not be as good as in those feedback control laws proposed in [BHM,BGSB].

2.2 Modeling and Control of Thermoacoustic Instabilities

We have obtained several important results during this reporting period for combustion control. We have been working with people in the Department of Mechanical Engineering at Louisiana State University and researchers in the Alstom Power, Inc. in Switzerland in applying robust and H_∞ control design in the combustion control problems. We have had great success in applying our control strategy. In particular, we have successfully demonstrated in experiments the benefits of our robust feedback control in the swirled combustion with both gaseous fuel and liquid fuel. These research are closely related to the aircraft engine design. The results will help in designing more efficient, more durable, and less polluted engines. One of the PI's students, D. Campos-Delgado (who has completed his PhD work in Spring 2001), had worked in Switzerland for the Summer 2000 on the gaseous fuel combustion engines. Our control strategies showed the clear advantages over the conventional phase delay control techniques that have been used in most of combustion experiments in the area. These tests were actually the first success in the area of using H_∞ robust control techniques for a large power combustor (>100KW). Most of the existing work are either computational or for very small power combustors. Another advantage of our design techniques over the conventional techniques such as phase delay control is that the controller seems to be very robust in the sense that the performance is mostly preserved under various operating conditions. We have also tested other design techniques using

online parameter search with great success. The following figures have shown some typical experimental data (scaled due to regulations of the company).



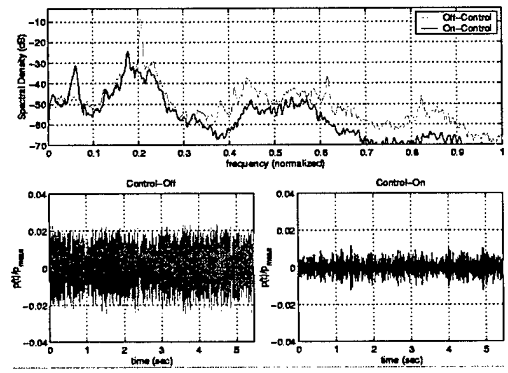
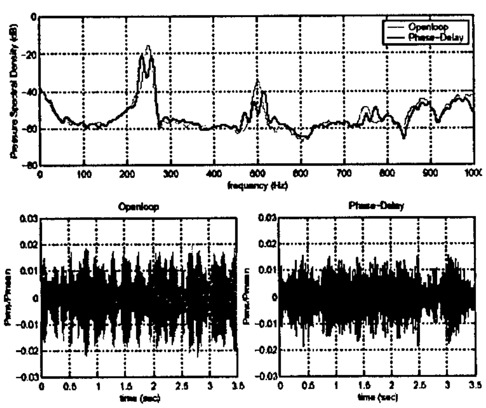


Figure 3: Conventional Phase-Delay Control Figure 4: H_∞ loop shaping control

(Gaseous fuel with DDV)

We have also worked on the liquid fuel combustion problem at LSU together with people in the Mechanical Engineering department for the last year or so. Our control strategies showed great potential in reducing the combustion oscillation and noise. Relatively speaking, we are less successful in the liquid fuel combustion where we have used automotive fuel injectors, which cannot generate proportional fuel with the control signals, in contrast with the experiments done in Alstom Power where direct drive valves (DDV) are used that can generate proportional control signals.



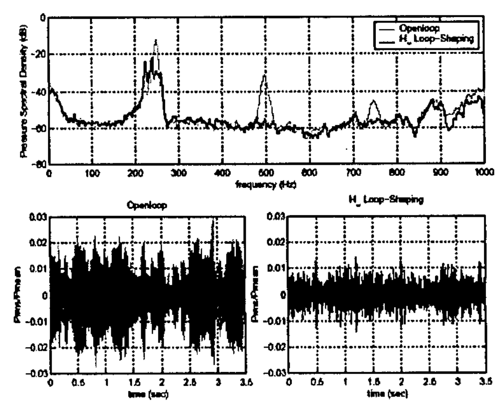


Figure 3: Conventional Phase-Delay Contro Figure 4: H_∞ loop shaping control

(Liquid fuel with automotive injectors)

2.3 H_∞ Based System Identification and Model Validation

System identification for robust control is a continuation of conventional system modeling and identification. Our project is aimed at both identification and quantification of the modeling errors. We have focused on linear time-invariant discrete-time systems,

and its transfer function matrix exists and is denoted by $P(z)$. It is assumed that $P(z)$ has size $p\times m$ with $p>m$ and admits a right normalized coprime factorization

$$P(z) = N(z)[D(z)]^{-1}, \qquad N^{\sim}N + D^{\sim}D = I_m$$

with $N(z)$ and $D(z)$ both analytic in the region $|z| \geq 1$. Let the generalized plant of $P(z)$ be defined by

$$G(z) := \begin{bmatrix} D(z) \\ N(z) \end{bmatrix} = \sum_{k=0}^{\infty} g_k z^{-k}$$

where $g_k \in \mathbf{R}^{q\times m}$, $q=p+m$. It is assumed that $G \in S$ where S is a strict subset of H_∞ that characterizes the *a priori* information of the true unknown plant. Modeling of $G(z)$ with error bounds in H_∞ norm is the key to H_∞ based loopshaping design. Hence we have developed a new identification algorithm, based on noisy experimental data of $P(z)$ to construct the generalized model $G(z)$, and to quantify the associated error bound. The results are reported in [G1].

Our second important contribution is the development of nearly interpolatory algorithm for H_∞ identification based on both time and frequency domain data. The features of our proposed algorithm include nearly optimal identification error bound in H_∞ norm, and much lower computational complexity in comparison with our early results on exact interpolatory algorithm reported in [XRGC]. See [GC] for more detailed information and discussion on our proposed nearly interpolatory algorithm.

Our third contribution in H_∞ identification is the worst-case asymptotic properties as reported in [CG]. The sample complexity of time and frequency-domain H_∞ identification problems has been estimated, which exhibits a polynomial growth requirement on the input data duration for the time-domain H_∞ identification problem and a linear growth rate of frequency response samples required for the frequency-domain H_∞ identification problem. The divergence behavior has also been established for linear algorithms for the time and frequency domain problems. The results extend previous work to more restricted sets of linear time-invariant systems with more refined *a priori* information, specifically imposed on the stability degree and the steady-state gain of the systems, thus demonstrating that no robustly convergent linear algorithms can exist even for a small set of exponentially stable systems.

Uncertainty model validation has been studied for stable systems by several authors [BF,C,SD]. We have extended existing work to unstable plants. The first one is on the uncertainty model described by normalized coprime factors. It has been shown in our work [G2] that a necessary condition is needed in order for coprime factor uncertainty systems not to be invalidated, contrast to the work in [BF]. We explored further the general uncertainty model in the form of linear fractional transform. We have shown that under a similar assumption to [C], a necessary and sufficient condition is obtained for unstable uncertainty models not to be invalidated, which generalizes the results in [C,SD].

Although we have focused on linear models, effort has been made to collaborate with the MIT compressor control group for identification of rotating stall dynamics using the experimental frequency domain data from the MIT compressor rig. We are still working on this important modeling problem for the compressor model, and will report our further results in the near future.

2.4 Fault Detection and Reconfigurable Control

Our most important contribution to fault detection and tolerance control is the proposal of a new feedback control architecture that has the potential to overcome many conflicting problems in standard feedback control. More importantly it provides a unified framework for robust and fault tolerance control. The results are reported in [ZR]. This new feedback control architecture uses the well-known Youla controller parameterization in a non-traditional way. The distinguished feature of our new controller architecture is that it shows structurally how the controller design for performance and robustness may be done separately. First of all a high performance controller K_0 can be designed using any method, and then a robustification controller Q, which is the Youla parameter can be designed to guarantee robust stability and performance using any standard robust control techniques. When there is no model uncertainty, the feedback system will be controlled solely by the high performance controller K_0 while the robustification controller Q will be active when there are model uncertainties or external disturbances. This controller architecture offers an excellent way to build the fault-tolerance control strategy based on normal working controllers.

Our second contribution is on reconfiguable control as reported in [WZS]. The rationale for the use of "reconfigurability" is that the measure is expected to reflect the plant's capability to allow restoration of performance in the presence of faults, through the application of either a passive or an active control strategy. The utility of reconfigurability is expected to facilitate both analysis and synthesis in relation to fault tolerant control. Reconfiguration reveals the potentiality as well as the limitation of the model used for fault tolerant control. Subsequently, measures could be taken in some applications to redesign and remodel the plant. One example of an earlier work with traces of synthesis flavor was reported in [M], where the placement of sensors and actuators for the purpose of an enhanced reliability was considered. In our work on fault tolerance and reconfigurable control [WZS], the background on the second order modes for stable systems helps us lead to the definition of reconfigurability. The concept of reconfigurability is introduced for linear time-invariant and stable plant models. The second order models and the concept of reconfigurability are then extended to include unstable systems by introducing some new characterization of controllability and observability. Moreover reconfigurability computation is carried out for two plant models drawn from some existing fault tolerant control literature. We also considered some possible extensions of the reconfigurability notion for more general plant models.

As an integrable part for fault tolerance and reconfigurable control, we have carried out research work on strong stabilization, where only stable feedback controllers are

allowed to use. One of the key issues in the controller design of the combustion system is the stability of the controller itself. Since the models obtained for the combustion process are mostly non-minimum phase, the H_∞ controller computed from the standard algorithms tends to be unstable which is not practically implementable in the combustion application. Thus an important problem is to find a way to compute a stable controller with minimum degradation of performance. We have proposed a technique for designing such stable H_∞ controllers. Similar to some methods in the existing literature, the proposed method also uses the parameterizations of all suboptimal H_∞ controllers so that the stable H_∞ design problem can be (conservatively) converted into another 2-block standard H_∞ problem. However, a weighting function is introduced in this method to alleviate the conservativeness of the previous formulations. Numerical examples are presented to demonstrate the effectiveness of the proposed method. We are now also exploring other numerical methods for this type of problems and our preliminary investigation shows that even better results can be obtained.

2.5 Robust Adaptive Control

Adaptive modeling and control algorithms for uncertainty systems are also our important research topics. In this research work, a novel idea, termed as *uncertainty equivalence principle*, is proposed, based on which an equivalent measure to the H_∞ norm is adopted for unmodeled dynamics using time-domain measurement data. Such an equivalent description for modeling errors is consistent with H_∞ based robust control, and allows H_∞ optimization to be successfully used in adaptive control to achieve robust stability and performance comparable to H_∞ control. Specifically two new adaptive control systems are proposed. The first tackles stable plants, employing the recursive least-squares (RLS) algorithm for adaptive model estimation, and weighted sensitivity minimization plus robust stabilization for adaptive controller design. While the second considers unstable plants, employing the total least-squares (TLS) algorithm for adaptive model estimation, and H_∞ loopshaping for adaptive controller design. Our results show that the two proposed adaptive control systems admit robust stability and performance asymptotically, provided that the estimated plant model converges. The results will be reported in 2002 IEEE Conference on Decision and Control.

2.6 Concluding Remarks

As summarized above, our research program has achieved great accomplishment during the past three years. These achievements are inseparable from the help and collaboration of the control group in the Wright Laboratory at the Wright-Patterson Air Force Base led by Dr. Siva Banda. Our most important research results are in compressor control, combustion control, fault detection and reconfigurable control, H_∞ based system identification and model validation, and robust adaptive control. However we also made contributions to time delay systems, important to our research program due to the

involvement of combustion instabilities with time-delay. We have made significant progress in the robust stability analysis and control of uncertain time delay systems. These types of systems are very common in the process control, for example, in our combustion control problem. We have derived the least conservative sufficient stability conditions by using various variations of small μ theorem. We have shown that the existing results in the literature are much more conservative than our conditions. Furthermore, robust control of uncertain delay systems can be studied by combining these stability criteria and the standard μ synthesis techniques. This research effort is a necessary step towards our total objective. We have also made reasonable progress for uncertain delay problems involving time varying sector nonlinearities and time invariant sector nonlinearities. In addition we also made significant contribution to multi-objective control and filtering. The most important results are mixed H_2 and H_∞ control problem. We have developed complete solution based on Nash game approach. Our other work include optimal channel equalization and multiuser detection in data networks such as CDMA wireless systems. Hence in summary we are happy to have contributed to not only DoD missions with Air Force problems as application platforms, but also other important research fields.

3. Personnel Supported

This research grant supported the PI, and the Co-PI for the summers of 1999, 2000, and 2001. It also supported partially three Ph.D. students, and five M.S. students for their thesis work. The details are as follows.

Principle Investigator: Guoxiang Gu

The PI has focused his work on both bifurcation based compressor control, and on system identification for robust control. He was supported with two-month salary for each summer of 1999, 2000, and 2001.

Co-Principle Investigator: Kemin Zhou

The Co-PI focused his work on modeling and control for engine combustion, on multi-objective optimal control, and on fault detection and reconfigurable feedback control. He was supported with two-month salary for each summer of 1999, 2000, and 2001.

Graduate Research Assistant: Ehab Badran

Ehab Badran is a Ph.D. student who graduated in May of 2002. He also obtained his M.S. degree in May of 2001. His Ph.D. dissertation was on system approach to optimal channel equalization, who has helped the PI to do numerical analysis and signal processing for compressor models. He has submitted two journal papers with the PI. He received 25% RA in first three months of 2002, and fall semester of 2001.

Graduate Research Assistant: Calin Belta

Calin Belta was an M.S. student who graduated in August 1999. His thesis work is on bifurcation stabilization and rotating stall control. He has published two journal papers and two conference papers. He received 25% RA support for summer of 1999.

Graduate Research Assistant: Daniel Campos-Delgado

Daniel Campos-Delgado was a Ph.D. student who graduated in August of 2001. His dissertation work is mainly on application of H_∞-based robust control to combustion control. He has published three journal papers, and five conference papers. He received 50% RA in summer of 2001.

Graduate Research Assistant: Jianqiang He

Jianqiang He was an M.S. student. He received his M.S. degree in December of 2001. His M.S. thesis is specialized on optimal detection for multiuser communication systems, applicable to CDMA wireless channels. He received 25%RA from August of 2000 to March 30 of 2002.

Graduate Research Assistant: Yunping Huang

Yunping Huang was a Ph.D. student who graduated in August of 2001. Her dissertation focuses on control of time delay systems. She has published two journal papers and two conference papers. She received 50% RA in summer of 2001.

Graduate Research Assistant: Lijuan Li

Lijuan Li is a Ph.D. student. She has performed her research in control of singular systems, with possible applications to rotating stall control in extreme cases. She received her M.S. degree in May of 2001. She has co-authored two journal papers with the PI. She received the 50% RA support for the calendar years of 2000, 2001, and first three months of 2002.

Graduate Research Assistant: Jingbo Wang

Jingbo Wang was an M.S. student. He got support from this project with 50% RA for the calendar years of 2000, and 25% RA for spring semester of 2001. He completed his M.S. degree on robust system identification in May of 2001.

Graduate Research Assistant: Zhongshan Wu

Zhongshan Wu was a Ph.D. student. He got support from this project with 50% RA for the calendar years of 2000, and 2001. He received 25% RA for the first three months of 2002. His research has focused on robust adaptive control with applications to active control of combustion. He completed his M.S. degree in August 2001.

4. Publications

Our research program in the past three years produced 30 journals publications, 1 book and 2 book chapters, and 28 conference papers, including those accepted for publications. These publications are listed as follows.

Book and Book Chapters

[1] J. Chen and G. Gu, *Control-Oriented System Identification --An H_∞ Approach*, John Wiley, 2000.

[2] G. Gu and A. Sparks, "Bifurcation stabilization with applications in jet engine control," in *Controlling Bifurcations and Chaos in Engineering Systems*, G. Chen Eds., CRC Press, 1999.

[3] K. Zhou, "H-Infinity Control," *The Encyclopedia of Electrical and Electronics Engineering*, vol. 9, pp. 94-106, John Wiley & Sons, Inc., 1999.

Journal Publications

[1] G. Gu, "Inner-outer factorization for strictly proper transfer matrices," Accepted by *IEEE Trans. Automat. Contr.,* 2002.

[2] D.U. Campos-Delgado and K. Zhou, "A parametric optimization approach to H_∞ and H_2 strong stabilization," Accepted by *Automatica*, 2002.

[3] D. U. Campos-Delgado, D. Allgood, K. Zhou, and S. Acharya, "Active control of combustion instabilities using model based controllers," Accepted by *Combustion Science and Technology*, 2002.

[4] D. U. Campos-Delgado, B. B. Schuermans, K. Zhou, C. O. Paschereit, E. Gallestey, and A. Poncet, "Thermoacoustic instabilities: modeling and control," *IEEE Transactions on Control Systems Technology*, accepted as a regular paper subject to revision.

[5] X. Chen and K. Zhou, "H_2 Gaussian filter on infinite time horizon", *IEEE Transaction on Circuits and Systems--Part I: Fundamental Theory and Application*, Vol. 49, No. 5, May 2002, pp. 674-679.

[6] G. Gu, ``Remarks on validation of uncertainty models using frequency response data," *IEEE Trans. Automat. Contr.*, vol. 47, 486-490, 2002.

[7] J. Chen and G. Gu, "Worst-case asymptotic properties of H_∞ identification," *IEEE Trans. Circuits and Syst.*, vol. 49, 437-446, 2002.

[8] D. U. Campos-Delgado and K. Zhou, "H_2 strong stabilization," *IEEE Transactions on Automatic Control*, Vol. 46, No. 12, pp. 1968-1972, 2001.

[9] X. Chen, A.G. Sparks, K. Zhou, and G. Gu, "Local robustness of stationary bifurcation control," *Latin American Applied Research*, 163-170, 2001.

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6. Interactions/Transitions and Others

[a.] Both PIs, have given numerous presentations in major control conferences, and been invited to give several seminars in different research institutes. Their students have also participated in conference activities to present their research results.

[b.] In the past three years, the PI Guoxiang Gu collaborated closely with the control group of Dr. Siva Banda and Dr. Andrew Sparks in WPAFB (Wright-Patterson Air Force Base). Two groups met each other yearly in major control conferences, and in WPAFB, which resolve the technical problem of rotating stall control for multi-mode compressor models. Several joint papers are presented in major control conferences and published in well-known technical journals. See the section of publications. The PI also

pro-actively sought the partnership with other researchers in the same field, including Dr. Jim Paduano at MIT. The PI Kemin Zhou has worked with people in the Department of Mechanical Engineering at Louisiana State University for last three years, where some navy air force projects involving combustion engine are conducted. We have successfully demonstrated in experiments the benefits of our robust feedback control in the swirled combustion with liquid fuel.

[c.] Technology Transitions: Since inception of our program, effort has been to make technology transition. Our activities in this regard are described as follows:

Compressor control.

Performer:	Professor Guoxiang Gu, and Mr. Calin Belta (RA). Telephone: (225) 578-5534
Customer:	Flight Dynamics Laboratory, Wright-Patterson Air Force Base
Contact	Dr. Andrew Sparks Telephone: (937) 255-8682
Results:	Feedback control laws for local stabilization of the multi-mode compressors models without distributed sensing.
Application:	Stability analysis and stabilization for rotating stall.

Combustion control.

Performer:	Professor Kemin Zhou, and Mr. D. Campos-Delgado (RA)
Telephone:	(225) 578-5533.
Customer:	Alstom Power, Inc., AAT-T4, 5400 Baden, Switzerland
Contact:	Mr. Bruno Schuermans
Telephone:	+41 564867061
Results:	New control design techniques using H_∞ based loop shaping in active control of swirled combustion with liquid fuel.
Application:	Suppression of the vibration in combustion.

[d.] New discoveries, inventions, or patent disclosures: None.

[e.] Honors/Awards: None.

7. Conclusion

During the past three years, our research program has accomplished more than it was initially planned. Our achievements include rotating stall and surge control, modeling and control of combustion instabilities, fault detection and configurable control, identification and model validation of uncertain systems as proposed, H_∞ based robust adaptive control. Our program also explored time-delay control, model reduction using optimal Hankel-norm approximation for discrete-time systems, optimal channel equalzation and multiuser detection that are outside the scope of this program. The research results were reported in 30 journal publications, 1 book, 2 book chapters, and 25

conference papers, and were summarized in this final report. For the past three years, three graduate students were trained at the Ph.D. level, and five at M.S. level who graduated with degrees. These students were partially supported by this grant, and most MS graduates remain working for their Ph.D. degrees. Considering the size of our program and limited amount of funding, this is a quite accomplishment for us in both research and in education. Our program was very fortunate to work under the AFOSR Control and Dynamics Program during our three-year period, and to have a strong tie with the control group in Wright Laboratory at Wright-Patterson Air Force Base led by Dr. Siva Banda. With the preparation of this research program and close collaboration with the control group at Wright-Patterson Air Force Base led by Dr. Siva Banda, we are well positioned to accomplish further research objectives in the interest of Air Force. Our control group at LSU is confident that our research program has the capability to contribute further to the DoD mission in the near future.

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